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FLUID MECHANICS

INFLUENCE OF SORET EFFECT, HEAT SOURCE, VISCOUS DISSIPATION, CHEMICAL REACTION, THERMAL RADIATION AND VARIABLE PERMEABILITY ON HEAT AND MASS TRANSFER THREE DIMENSIONAL FREE CONVECTIVE MHD FLOW THROUGH POROUS MEDIUM

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ABSTRACT: In the present study, the influence of Soret effects, Heat Source, Thermal Radiation, Viscous Dissipation and Chemical Reaction on three-dimensional free convective MHD flow through porous medium with variable permeability was examined. The dimensionless governing equations were solved analytically by Multiple Regular Perturbation Law. The effects of several flow parameters affecting velocity, temperature and concentration were explained and discussed graphically. The expressions for the skin friction, Nusselt number and Modified Nusselt Number profiles were formulated and discussed with the help of tables. It is observed that the velocity of the fluid initially increases and then decreases with increase of y but it showed reverse behaviour with large increase in radiation parameter (R).

KEY WORDS: Soret effects, Heat Source, Thermal Radiation, Viscous Dissipation, Chemical Reaction.

1 INTRODUCTION

Three dimensional free convective MHD flow through porous medium plays an important role in the field of science, technology and engineering such as the process of purification and filtration in the area of chemical engineering, ground water pollution, evaporative cooling air conditioners, process of magnetic material, solar collectors and the study of seeping water in the river basin. In view of these applications, a series of investigations have been made by many researchers [1–3] into the three dimensional convective flow past a vertical porous plate. T. Singh and M.G. Gorla [4] have

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studied the three dimensional MHD flow and heat transfer through porous medium bounded by a porous vertical surface with heat source and variable permeability. J.S. Dhiman, T. Singh and M.G. Gorla [5] have further studied the problem of three dimensional free convective MHD flow with heat and mass transfer through a porous medium with variable permeability. K.D. Singh, K. Chand and S. Sharma [6] again studied heat and mass transfer in an unsteady MHD convective flow through a porous medium bounded by vertical porous channel in the presence of radiative heat and hall current. The problem of MHD free convective flow through porous medium in the presence of hall current, radiation and thermal diffusion was examined in Ref. [7]. S.M. Ibrahim, T.S. Reddy and P. Roja [8] have reported radiation effects on unsteady MHD free convective heat and mass transfer flow of past a vertical porous plate embedded in a porous medium with viscous dissipation. B.P. Reddy [9] has investigated MHD flow over a vertical moving porous plate with viscous dissipation by considering double diffusive convection in the presence of chemical reaction. The effect of MHD convective heat and mass transfer flow of a Newtonian fluid past a vertical porous plate with chemical reaction, radiation absorption and thermal diffusion studied in Ref. [10]. P. Gurivireddy et al. [11] have analysed the thermal diffusion effect on MHD heat and mass transfer flow past a semi-infinite moving vertical porous plate with heat generation and chemical reaction. The effect of MHD mass transfer flow past a vertical porous plate embedded in a porous medium in a slip flow regime with the influence of hall current and thermal diffusion analysed [12]. V. Malapati and V.L. Dasari [13] have investigated the problem of Soret and chemical reaction effects on the radiative MHD flow from an infinite vertical porous plate. S.M. Hussaina et al. [14] have reported the free convective heat transfer with hall effects, heat absorption and chemical reaction over an accelerated moving plate in a rotating system. K.V.B. Rajakumar et al. [15] have studied the radiation, dissipation and dufour effects on MHD free convective casson fluid flow through a vertical oscillatory porous plate with ion-slip current. Hydromagnetic oscillatory flow and heat transfer in dusty viscoelastic fluid through porous medium in an inclined channel in the presence of thermal radiation and heat sink have been investigated in Ref. [16]. T. Singh and H. Pal [17] have investigated the influence of MHD with radiation, chemical reaction and Soret effects on free convective heat and mass transfer flow through a highly porous medium. R.P. Sharma et al. [18] have analysed the buoyancy effects on unsteady MHD chemical reacting and rotating fluid flow past a plate in a porous medium. Perturbation analysis of thermophoresis, hall current and heat source on flow dissipative aligned convective flow about an inclined studied by G. Dharmaiah, O.D. Makinde and K.S. Balmurugan [19]. Ch.B. Rani et al. [20] have presented hall and ion slip effects on AG-water based MHD Nano fluid flow over a semi-infinite vertical plate embedded in porous medium. V. Sharma et al. [21] have

investigated Rayleigh–Taylor instability of superposed dusty Jeffrey fluids through porous medium with interfacial surface tension.

Remembering every one of these realities in this work the effect of Soret effect on heat and mass transfer three dimensional free convective MHD flow through porous medium bounded by a porous vertical plate with heat source, viscous dissipation, chemical reaction, thermal radiation and variable permeability was investigated. The multiple regular perturbation technique is employed to solve dimensionless governing equations.

2 Mathematical Formulation

An unsteady three-dimensional free convective MHD flow of a viscous electrically conducting fluid with heat and mass transfer flow through a highly porous medium by an infinite vertical porous plate with constant suction, heat source, viscous dissipation, chemical reaction, thermal radiation and variable permeability is considered along $x^* - y^*$ plane with x^*-axis taken along the plate in the upward direction. The y^*-axis is taken normal to the plane. A magnetic field B_0 of uniform nature is implemented in the direction of x^*-axis. The permeability of the porous medium is assumed to be of the form

$$K\left(Z^*\right) = K_0^* \left\{1 + \varepsilon \cos\left(\frac{\pi z^*}{l}\right)\right\}^{-1}$$

where, K_0^* is the mean permeability of the medium, l is the wave length of permeability distribution and ε $(\ll 1)$ is the amplitude of the permeability variation. The problem becomes three-dimensional due to such a permeability variation. u^*, v^* and w^* are the velocity components in the directions of x^*, y^* and z^* respectively. T^* and C^* are the temperature and concentration of the fluid. The periodic suction velocity is considered to be of the form

$$v^* = -V\left\{1 + \varepsilon \cos\left(\frac{\pi z^*}{l}\right)\right\},$$

where, V is the mean suction velocity.

Flow configuration of the problem is shown in Fig. 1.

Within the frame work of these assumptions, the governing equations in dimensionless form, using the radiative heat flux term Rosseland approximation [11] $q_r^* = -\dfrac{4\sigma_s^*}{3ke^*}\dfrac{\partial T^{*4}}{\partial y^*}$ and Taylor series $T^* \cong 4T^*T_\infty^{*3} - 3T_\infty^*$ are

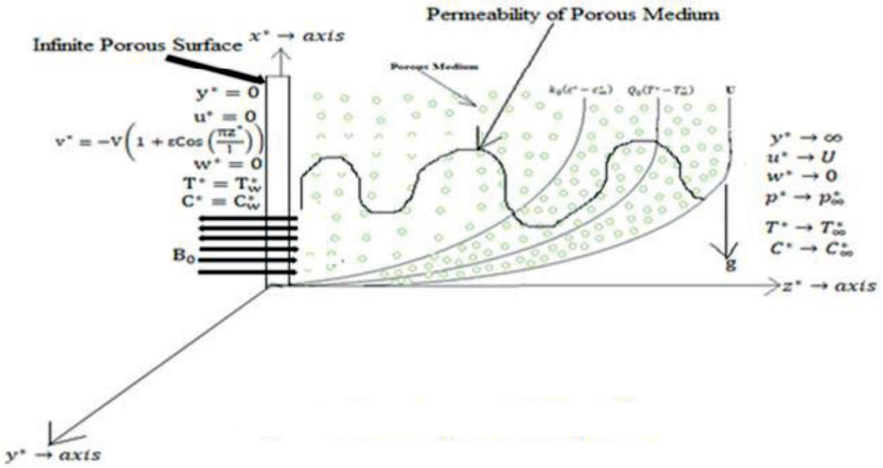

Fig. 1. Flow configuration of the problem.

EQUATION OF CONTINUITY

$$\frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0\,. \tag{1}$$

EQUATION OF MOTION

$$v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = Gr\,Re\theta + Gm\,Re\,C + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{1}{Re}\frac{1+\varepsilon\cos\pi z}{K_0}(u-1) - \frac{M^2}{Re}u \tag{2}$$

$$v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{1}{Re}\frac{1+\varepsilon\cos\pi z}{K_0}v - \frac{M^2}{Rr}v \tag{3}$$

$$v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re}\left(\frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{1}{Re}\frac{1+\varepsilon\cos\pi z}{K_0}w - \frac{M^2}{Rr}w\,. \tag{4}$$

EQUATION OF ENERGY

$$\frac{\partial^2\theta}{\partial z^2} + \left(\frac{3R+4}{3R}\right)\frac{\partial^2\theta}{\partial y^2} - PrRe\left(v\frac{\partial\theta}{\partial y} + w\frac{\partial\theta}{\partial z}\right) + 2\lambda^2 PrEc\left\{\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right\} + PrEc\left\{\left(\frac{\partial u}{\partial z}\right)^2 + 2\left(\frac{\partial u}{\partial y}\right)^2\right\} + \lambda^2 PrEc\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + S\theta = 0\,. \tag{5}$$

DIFFUSION EQUATION

$$v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{1}{Sc}\frac{1}{Re}\left(\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}\right)^2-Kr\,Re\,C+\frac{Su}{Re}\frac{\partial^2\theta}{\partial z^2}\,. \tag{6}$$

The corresponding dimensionless boundary conditions are:

$$\begin{aligned} &y=0,\ u=0,\ v=-\left(1+\varepsilon\cos\pi z\right),\ w=0,\ \theta=1,\ C=1\,,\\ &\text{and}\ \ y\to\infty,\ u\to 1,\ w\to 0,\ p\to p_\infty,\ \theta\to 0,\ C\to 0\,. \end{aligned} \tag{7}$$

3 METHOD OF SOLUTION

Equations (1) to (6) are solved under the boundary conditions (7). In view of the boundary conditions, u, v, w, p and θ can be expand in the powers of ε as given below:

$$F\left(y,z\right)=F_0\left(y\right)+\varepsilon F_1\left(y,z\right)+\varepsilon^2 F_2\left(y,z\right)+\cdots\,, \tag{8}$$

where F stands for any one of u, v, w, p, and θ.

When $\varepsilon=0$, the problem reduces to the two dimensional free convective flow through a porous medium with constant suction and constant permeability

$$\frac{dv_0}{dy}=0\,, \tag{9}$$

$$\frac{d^2u_0}{dy^2}+Re\frac{du_0}{dy}-\left(\frac{1}{k_0}+M^2\right)u_0=-Gr\,Re^2\theta_0-Gm\,Re^2C_0-\frac{1}{K_0}\,, \tag{10}$$

$$\left(\frac{3R+4}{3R}\right)\frac{d^2\theta_0}{dy^2}+Pr\,Re\frac{d\theta_0}{dy}+2Pr\,Ec\left(\frac{du_0}{dy}\right)^2+S\theta_0=0\,, \tag{11}$$

$$\frac{d^2C_0}{dy^2}+Sc\,Re\frac{dC_0}{dy}-Kr\,ScRe^2C_0=0\,. \tag{12}$$

The corresponding dimensionless boundary conditions are

$$\begin{aligned} &y=0,\ u_0=0,\ v_0=-1,\ \theta_0=1,\ C_0=1\\ &\text{and}\ \ y\to\infty,\ u_0\to 1,\ p_0\to p_\infty\ \ \theta_0\to 0,\ C_0\to 0\,. \end{aligned} \tag{13}$$

Solution of equations (9) and (12) under boundary conditions (13) are given below:

$$v_0=-1\ \ (\text{constant}), \tag{14}$$

$$C_0=\exp\left\{-\left(\frac{Sc\,Re+\sqrt{Sc^2Re^2+4Kr\,Sc\,Re^2}}{2}\right)y\right\}\,. \tag{15}$$

The equations (10) and (11) are ordinary second order coupled differential equations and solved under the boundary conditions (13). Since, the Eckert number Ec is small for incompressible fluid flows, $u_0(y)$ and $\theta_0(y)$ can be expanded in the powers of Ec as given below:

$$u_0(y) = u_{00}(y) + Ec\,u_{01}(y) + O\left(Ec^2\right), \tag{16}$$

$$\theta_0 = \theta_{00}(y) + Ec\,\theta_{01}(y) + O(Ec^2). \tag{17}$$

Substituting (16) and (17) into the equations (10) to (11) and equating the coefficients of like powers of Ec, we get a set of ordinary second order differential equations which are solved under the corresponding boundary conditions. Hence, the solutions of u_{00}, u_{01}, θ_{00}, θ_{01} are known, whose expressions are not included here for the sake of brevity.

When $\varepsilon \neq 0$ substituting (8) and non-dimensional equation $K(Z) = \dfrac{K_0}{1+\varepsilon\cos(\frac{\pi z}{l})}$ in to equations (1) to (6) and comparing the coefficients of identical powers of ε, neglecting those of ε^2, ε^3 etc. Also, take help of $v_0 = -1$, $w_0 = 0$ and $p_0 = p_\infty$, we have

$$\frac{\partial v_1}{\partial y} + \frac{\partial w_1}{\partial z} = 0 \tag{18}$$

$$v_1\frac{du_0}{dy} - \frac{\partial u_1}{\partial y} = Gr\,Re\,\theta_1 + Gm\,Re\,C_1 + \frac{1}{Re}\left(\frac{\partial^2 u_1}{\partial y^2} + \frac{\partial^2 u_1}{\partial z^2}\right) - \frac{1}{Re}\left[\frac{(u_0-1)\cos\pi z + u_1}{K_0}\right] - \frac{M^2}{Re}u_1 \tag{19}$$

$$-\frac{\partial v_1}{\partial y} = -\frac{\partial p_1}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v_1}{\partial y^2} + \frac{\partial^2 v_1}{\partial z^2}\right) + \frac{1}{Re}\frac{\cos\pi z - v_1}{K_0} - \frac{M^2}{Re}v_1 \tag{20}$$

$$-\frac{\partial w_1}{\partial y} = -\frac{\partial p_1}{\partial z} + \frac{1}{Re}\left(\frac{\partial^2 w_1}{\partial y^2} + \frac{\partial^2 w_1}{\partial z^2}\right) - \frac{1}{Re}\frac{1}{K_0}w_1 - \frac{M^2}{Re}w_1 \tag{21}$$

$$\frac{\partial^2\theta_1}{\partial z^2} + \left(\frac{3R+4}{3R}\right)\frac{\partial^2\theta_1}{\partial y^2} + Pr\,Re\left(\frac{\partial\theta_1}{\partial y} - v_1\frac{d\theta_0}{dy}\right) + 4Pr\,Ec\frac{du_0}{dy}\frac{\partial u_1}{\partial y} + S\theta_1 = 0 \tag{22}$$

$$v_1\frac{dC_0}{dy} - \frac{\partial C_1}{\partial y} = \frac{1}{Sc}\frac{1}{Re}\left(\frac{\partial^2 C_1}{\partial y^2} + \frac{\partial^2 C_1}{\partial z^2}\right) - KrReC_1 + \frac{Su}{Re}\frac{\partial^2\theta_1}{\partial z^2}. \tag{23}$$

The corresponding dimensionless boundary conditions are

$$\begin{aligned} &y = 0,\ u_1 = 0,\ v_1 = -\cos\pi z,\ w_1 = 0,\ \theta_1 = 0,\ C_1 = 0 \\ \text{and}\ &y \to \infty,\ u_1 \to 0,\ w_1 \to 0,\ p_1 \to 0,\ \theta_1 \to 0,\ C_1 \to 0 \end{aligned} \tag{24}$$

The equations (18) to (23) are independent of the main flow and temperature field of the fluid in view of the boundary conditions, apply separation of variable technique, it is assumed that

$$v_1(y,z) = -v_{11}(y)\cos\pi z\,, \tag{25}$$

$$w_1(y,z) = \frac{1}{\pi}\frac{d}{dy}(v_{11}(y))\sin\pi z\,, \tag{26}$$

$$p_1(y,z) = p_{11}(y)\cos\pi z\,. \tag{27}$$

The equation of continuity (18) satisfied automatically.

Substituting the expressions (25) to (27) into the equations (20) and (21) and in boundary condition (24), we get the solution of v_1, w_1 and p_1 under modified boundary condition whose expressions are not included here for the sake of brevity.

For the solution of main flow, the temperature and concentration fields we assume u_1, θ_1 and C_1 as

$$u_1(y,z) = u_{11}(y)\cos\pi z\,, \tag{28}$$

$$\theta_1(y,z) = \theta_{11}(y)\cos\pi z\,, \tag{29}$$

$$C_1(y,z) = C_{11}(y)\cos\pi z\,. \tag{30}$$

Using (28) to (30); (19), (22) and (23) becomes

$$\frac{d^2u_{11}}{dy^2} + Re\frac{d}{dy}u_{11} - \left(\pi^2 + \frac{1}{k_0} + M^2\right)u_{11} + Gr\,Re^2\theta_{11} + GmRe^2C_{11} + Re\,v_{11}\frac{d}{dy}u_0 - \frac{u_0 - 1}{k_0} = 0\,, \tag{31}$$

$$-\pi^2\theta_{11} + \left(\frac{3R+4}{3R}\right)\frac{d^2\theta_{11}}{dy^2} + PrRe\frac{d\theta_{11}}{dy} + PrRev_{11}\frac{d}{dy}\theta_0 + 4Pr\,Ec\frac{du_0}{dy}\frac{du_{11}}{dy} + S\theta_{11} = 0\,, \tag{32}$$

$$\frac{d^2C_{11}}{dy^2} + Sc\,Re\frac{dC_{11}}{dy} - \left(\pi^2 + Sc\,Re^2Kr\right)C_{11} + Sc\,Re\,v_{11}\frac{dC_0}{dy} - Sc\,Su\pi^2\theta_{11} = 0\,, \tag{33}$$

The corresponding boundary conditions are

$$\begin{aligned} &y = 0,\ u_{11} = 0,\ \theta_{11} = 0,\ C_{11} = 0 \\ &y \to \infty,\ u_{11} \to 0,\ \theta_{11} \to 0,\ C_{11} \to 0 \end{aligned} \tag{34}$$

The equations (31) to (33) are second order coupled differential equations and solved under the boundary conditions (34).

Now, expanding $u_{11}(y)$, $\theta_{11}(y)$ and $C_{11}(y)$ in the powers of Ec as given below:

$$u_{11} = u_{110} + Ec\,u_{111} + Ec^2 u_{112} + \cdots, \tag{35}$$

$$\theta_{11} = \theta_{110} + Ec\,\theta_{111} + Ec^2\theta_{112} + \cdots, \tag{36}$$

$$C_{11} = C_{110} + Ec\,C_{111} + Ec^2 C_{112} + \cdots. \tag{37}$$

Using (16) and (17), substituting (35) to (37) into the equations (31) to (33) and in boundary conditions (34), we get modified equations in u_{110}, u_{111}, θ_{110}, θ_{111}, C_{110} and C_{111} including boundary conditions.

Using the expression of u_{00}, u_{01}, θ_{01}, C_0, v_{11} and modified boundary conditions, we get the values of u_{110}, u_{111}, θ_{110}, θ_{111} and C_{110}, C_{111} whose expressions are not included here for the sake of brevity.

The value of velocity field u(y, z), temperature field $\theta(y,z)$ and concentration field C(y, z) are given below:

$$u(y,z) = [u_{00} + Ec\,u_{01}] + \varepsilon\cos\pi z[u_{110} + Ec\,u_{111}], \tag{38}$$

$$\theta(y,z) = [\theta_{00} + Ec\,\theta_{01}] + \varepsilon\cos\pi z[\theta_{110} + Ec\,\theta_{111}], \tag{39}$$

$$C(y,z) = [C_{00} + Ec\,C_{01}] + \varepsilon\cos\pi z[C_{110} + Ec\,C_{111}]. \tag{40}$$

SKIN-FRICTION COEFFICIENT

Knowing the velocity field, we obtained the expression for the skin-friction in the x^*-direction in the non-dimensional forms

$$\tau_x = \frac{\tau_x^*}{\rho UV} = \frac{\vartheta}{Vl}\left(\frac{\partial u}{\partial y}\right)_{y=0} = \frac{1}{Re}\left[\left\{\left(\frac{\partial u_{00}}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial u_{01}}{\partial y}\right)_{y=0}\right\} + \varepsilon\left\{\left(\frac{\partial u_{110}}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial u_{111}}{\partial y}\right)_{y=0}\right\}\cos\pi z\right]. \tag{41}$$

NUSSELT NUMBER

Knowing the temperature field, the expression for the rate of heat transfer in terms of the Nusselt number is given by

$$Nu = -\frac{q^*}{\rho V C_p\,(T_w^* - T_w^*)} = \frac{k}{\rho V C_p l}\left(\frac{\partial\theta}{\partial y}\right)_{y=0} = \frac{1}{Re\,Pr}\left[\left\{\left(\frac{\partial\theta_{00}}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial\theta_{01}}{\partial y}\right)_{y=0}\right\} + \varepsilon\left\{\left(\frac{\partial\theta_{110}}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial\theta_{111}}{\partial y}\right)_{y=0}\right\}\cos\pi z\right]. \tag{42}$$

MODIFIED NUSSELT NUMBER

Knowing the concentration field, the expression for the rate of mass transfer in terms of modified Nusselt number is given by

$$(43)\quad Nu_1 = -\frac{q_1^* D}{\rho V C_p\,(T_w^* - T_w^*)} = \frac{D}{Vl}\left(\frac{\partial C}{\partial y}\right)_{y=0}$$
$$= \frac{1}{Re\,Sc}\left[\left(\frac{\partial C_0}{\partial y}\right)_{y=0} + \varepsilon\cos\pi z\left\{\left(\frac{\partial C_{110}}{\partial y}\right)_{y=0} + Ec\left(\frac{\partial C_{111}}{\partial y}\right)_{y=0}\right\}\right].$$

4 RESULTS AND DISCUSSION

In the present problem three dimensional free convectional MHD flow through porous medium with variable permeability in the presence of heat source, viscous dissipation, chemical reaction, thermal radiation and Soret effect was analysed by the perturbation technique. In this problem, the values of various physical parameters are selected as: $Pr = 0.71$, $Sc = 0.6$, $Su = 0.1$, $Ec = 0.001$, $Kr = 0.8$, $R = 2$, $Re = 2$, $Ra = 1$, $Gr = 2$, $Gm = 4$, $K = 0.2$, $M = 2$, $k_0 = 4$, $S = 0.3$, $t = 1$, $n = 0.5$, $\varepsilon = 0.2$ $A = 0.5$ $U = 0.5$, $\lambda = 1.4$, $\varphi = 0.43$, $\pi = 3.14$.

The basic purpose of the study was to analyse the effect of various said parameters on three dimensional free convectional MHD flow through a porous medium with variable permeability. The data was analysed graphically with the help of analytical software origin 18. The effects of various flow parameters on velocity, temperature and concentration streams are shown graphically in Figs. 2 to 20. Skin friction (τ_w) Nusselt number (Nu) and Modified Nusselt number (Nu_1) are tabulated in Table 1.

VELOCITY

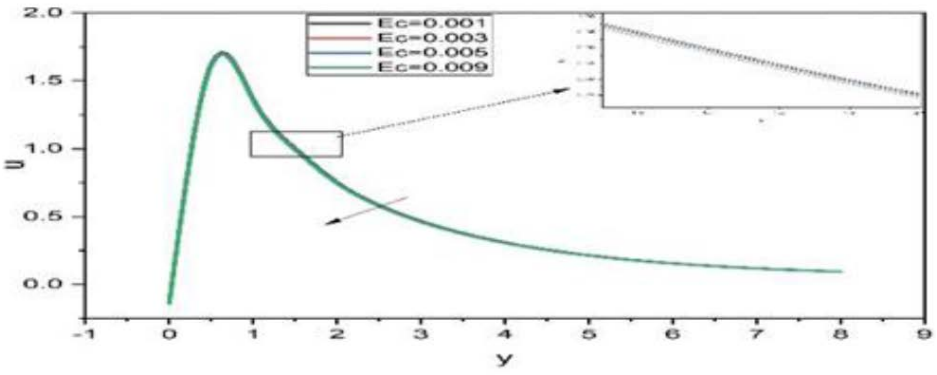

Fig. 2. Effect of Ec for different values on Velocity.

Table 1. Effect of Pr, Sc, Su, Ec, Kr, Re, R, Ra, Gr, Gm, K, M and S on skin friction (τ_ω), Nusselt number (Nu) and Modified Nusselt number (Nu_1)

Pr	Sc	Su	Ec	Kr	Re	R	Ra	Gr	Gm	K	M	S	τ_ω	Nu	Nu_1
0.71	0.60	0.1	0.001	0.8	2	2	1	2	4	0.2	2	0.30	8.806187	-0.30465	-1.98739
5													1.306807	-0.18924	-2.06776
7													6.893676	0.372784	-2.06197
11.62													8.861197	-0.38532	-2.0783
	0.42												-27.2419	-0.46847	-2.14587
	0.81												5.254111	-0.31439	-1.87939
	0.94												6.480607	-0.25355	-1.84018
		0.3											8.783736	-0.30598	-1.98772
		0.7											8.738833	-0.30866	-1.98838
		1.0											8.705155	-0.31067	-1.98887
			0.003										8.848974	-0.26124	-1.99699
			0.005										8.891762	-0.21784	-2.00659
			0.009										8.977336	-0.13103	-2.02579
				2									1.981.52	-0.3039	-2.66599
				5									1.524787	-0.32645	-3.74799
				10									0.166152	-0.33227	-4.96668
					3								8.206391	-0.39729	-2.00513
					4								7.698301	0.788461	-1.92694
					5								15.63971	3.105316	-2.14649
						4							8.148488	-0.50144	-1.98293
						6							8.032191	-0.59666	-1.99618
						8							9.388292	-1.26991	-1.25179
							5						8.806187	-0.30465	-1.98739
							10						8.806187	-0.30465	-1.98739
							15						8.806187	-0.30465	-1.98739
								1					8.657186	-0.30505	-1.98746
								3					8.952758	-0.30719	-1.98704
								4					9.100311	-0.31368	-1.9865
									2				3.996079	-0.32295	-1.98337
									3				6.399446	-0.31504	-1.98509
									5				11.21676	-0.2918	-1.99027
										0.4			8.806187	-0.30465	-1.98739
										0.6			8.806187	-0.30465	-1.98739
										0.8			8.806187	-0.30465	-1.98739
											4		-0.65139	-0.33136	-1.9025
											6		-0.34426	-0.33057	-1.86656
											8		-0.83809	-0.33079	-1.84894
												0.10	8.926956	-2.08565	-2.0253
												0.15	8.316662	-0.44495	-1.98354
												0.25	8.565888	-0.39737	-1.98579

For different values of Eckert number (Ec), the variation in velocity profile with y is plotted in Fig. 2. Eckert number is a dimensionless parameter, physically a measure of frictional heat in the system and used in MHD to characterize the relative importance of kinetic energy to thermal energy in a flowing fluid. Here, we find that the increase in the values of Eckert number (Ec) leads to decrease in velocity.

Generally increase in Eckert number increases the velocity of flowing fluid but here inverse effect shows the dominance of thermal energy dissipation due to friction, viscous dissipation over gain in kinetic energy.

Figure 3 shows the effects of Solutal Grashoff number (Gm) on the fluid velocity. The Solutal Grashoff number (Gm) is the ratio of the buoyancy force due to spatial variation in fluid density to the restraining force due to the viscosity of the fluid. As expected, it is revealed from the graph that the fluid velocity increases with increase in Gm. As the value of Gm number is greater than 1 the natural convection caused by the concentration difference is a dominant factor in the fluid flow. It indicates that the buoyancy forces resulting from solute differences are significant compared to viscous forces.

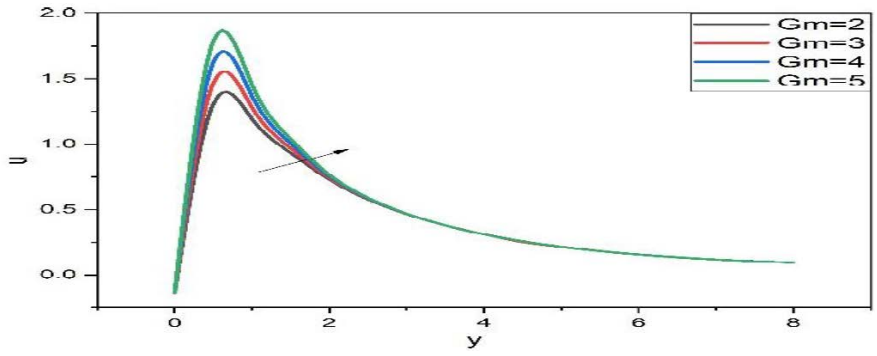

Fig. 3. Effect of Gm for different values on velocity.

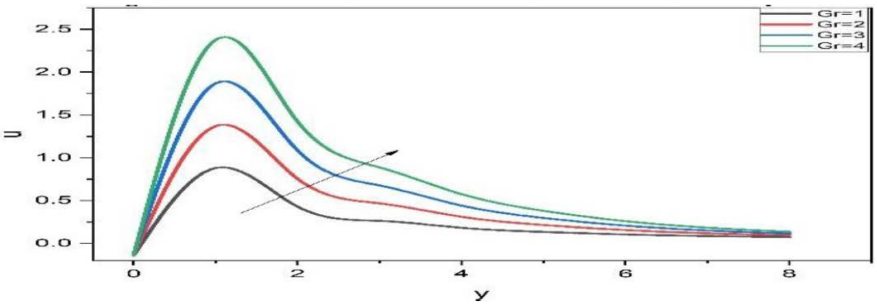

Fig. 4. Effect of Gr for different values on velocity.

Figure 4 represents the variation of fluid velocity with y for different values of Grashof number (Gr). It is observed that velocity increases with increase in Gr due to improvement in the buoyancy force as a result of significant temperature differences compared to viscous forces. In this case the natural convection is enhanced, leading to increased fluid velocity. These results are found to be in good agreement with the existing results of many researchers.

The influence of the permeability parameter (K_0) on the velocity profile with y is shown in Fig. 5. From this figure it is seen that the velocity decreases with increase in K_0 up to $y = 1$ and approximately at $1 < y < 2$ velocity increases with increase in K_0 and for $y > 2$ velocity again shows reverse behaviour with increase in K_0.

Parameability represents the resistnace to the flow of fluid reciprocaly, i.e., higher permibility means low resisitance. In porous media, the velocity profile is generally

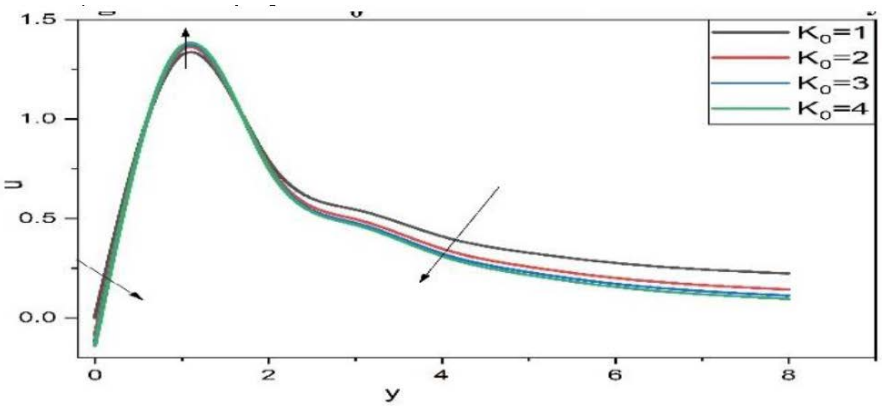

Fig. 5. Effect of K_0 for different values on velocity.

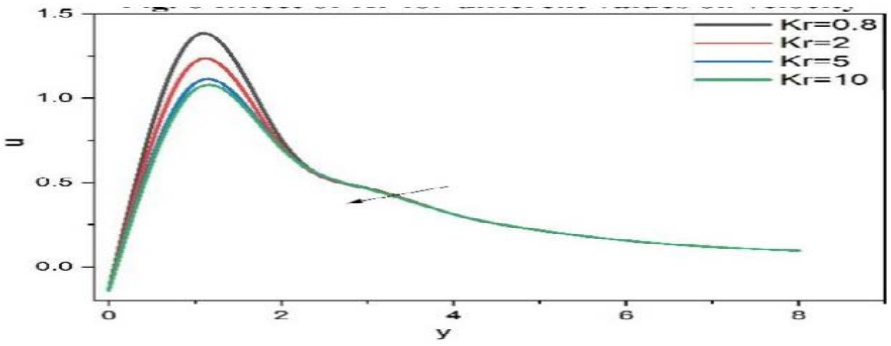

Fig. 6. Effect of Kr for different values on velocity.

non-uniform. The fluid flows faster in regions of higher permeability and slower in region of lower permeability. This results in a varying velocity profile within the porous medium.

Figure 6 shows the effects of chemical reaction parameter (Kr) on the variation of velocity profiles with y. From this figure it can be concluded that fluid velocity is diminishing with increase in Kr. The nature of the chemical reaction i.e. exothermic or endothermic leads to change in temperature and subsequently variation in fluid density and viscosity, affecting the velocity profile.

Figure 7 illustrate the variation of fluid velocity with y for different values of Hartmann number (M). The velocity of fluid appears reducing with expanding magnetic parameter. It has a pronounced effect on the velocity profile of a conducting fluid. As the Hartmann number increases, the flow tends to become more laminar and ordered with reduced turbulence. In moderate range ($1 < M < 10$) the fluid flow tends to become more ordered and laminar.

The effect of the different values of radiation parameter (R) on velocity profile with y is shown in Fig. 8. Here, it is evident that the velocity decreases with the increase in radiation parameter but with large increase in radiation parameter velocity profile reverse its behaviour. The radiation parameter defines the relative contribution of conduction heat transfer to thermal radiation transfer. A high value of radiation parameter ($R = 8$) indicates the dominance of radiative heat transfer and consequently decrease in velocity of fluid.

The velocity profile with y is plotted in Fig. 9 for different values of cross-flow Reynolds number (Re). From Fig. 9, it is observed that the velocity of the fluid increases sharply with the increase of Re up to $y = 1.5$ and from $y > 1.5$ it starts decreasing. The Reynolds number (Re) helps to predict flow patterns in different

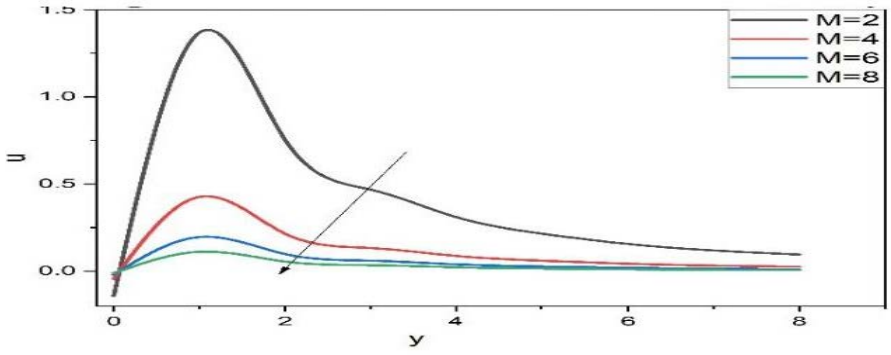

Fig. 7. Effect of M for different values on velocity.

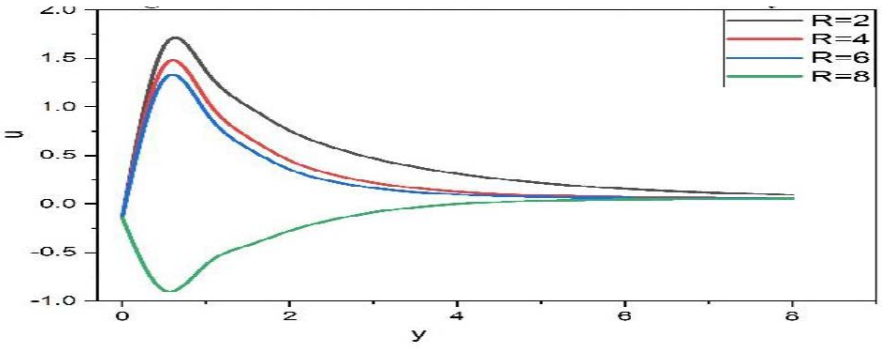

Fig. 8. Effect of R for different values on velocity.

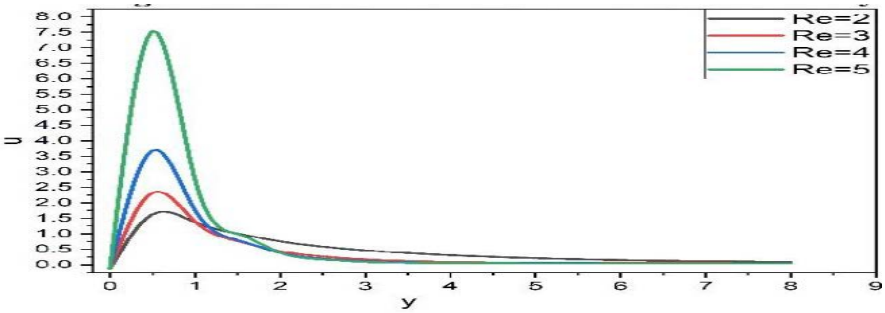

Fig. 9. Effect of Re for different values on velocity.

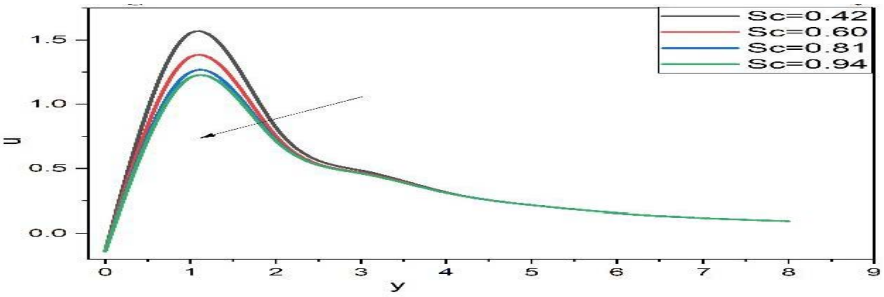

Fig. 10. Effect of Sc for different values on velocity.

fluid flow situations. The transition from laminar to turbulent flow has prominent impact on heat and mass transfer, pressure drop and mixing in fluid system.

From the graph of Fig. 10, it is observed that velocity of fluid decreases with increase in Schmidt number (Sc). Schmidt number is a dimensionless number and is used to characterize fluid flows in which there are simultaneous momentum and

mass diffusion convection process. It indicates the transition of dominance of mass transfer (molecular diffusion) to momentum transfer (viscous forces).

TEMPERATURE

It is inferred from Fig. 11 that the fluid temperature increases due to increase in Eckert number (Ec). It reflects the relative dominance of kinetic energy (due to fluid motion to internal energy (thermal energy) in a fluid flow.

For different values of Prandtl number (Pr), the temperature profile is plotted in Fig. 12, here we find that at $Pr = 0.5$ temperature of the fluid increases up to $y = 0.06$, then after it decreases sharply. At $Pr = 7$ temperature of the fluid decreases sharply. At $Pr = 11.62$ temperature of the fluid increasing in the beginning up to $y = 0.01$ and then after it starts decreasing.

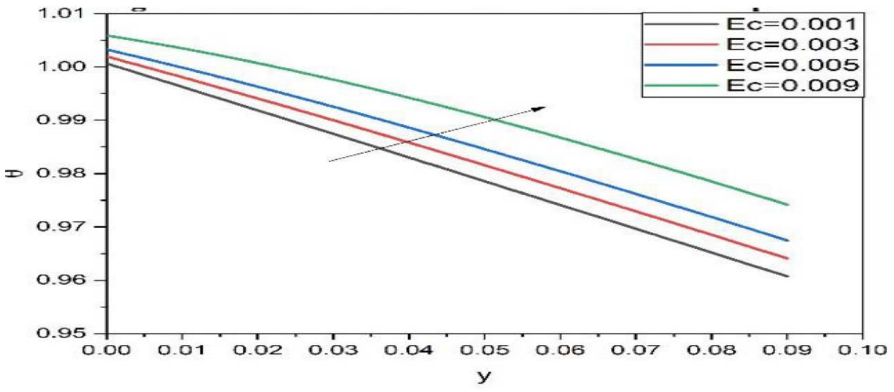

Fig. 11. Effect of Ec for different values on temperature.

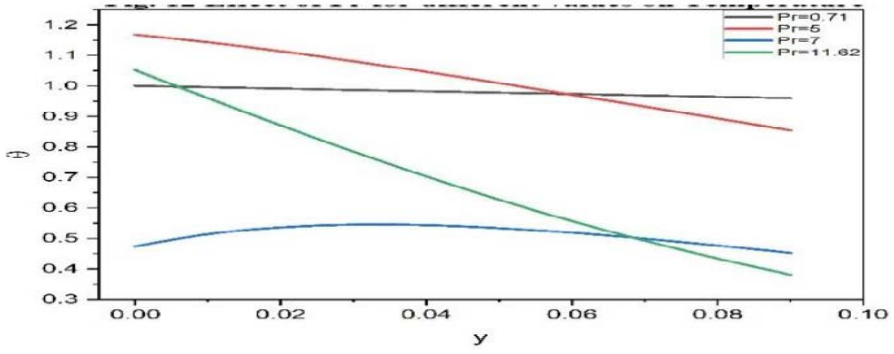

Fig. 12. Effect of Pr for different values on temperature.

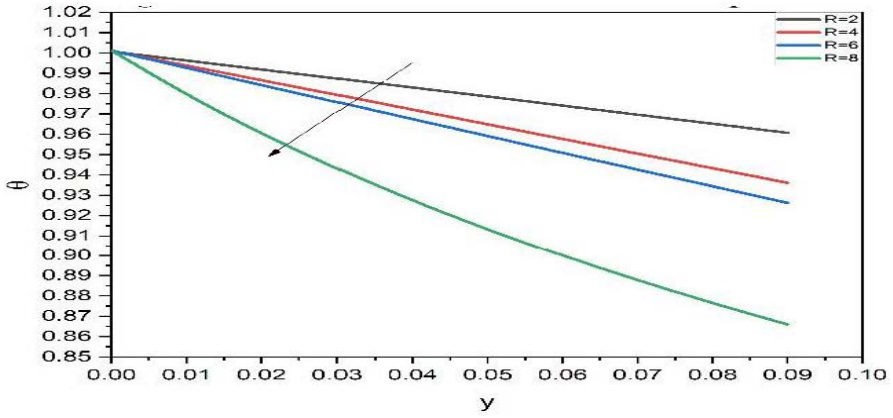

Fig. 13. Effect of R for different values on temperature.

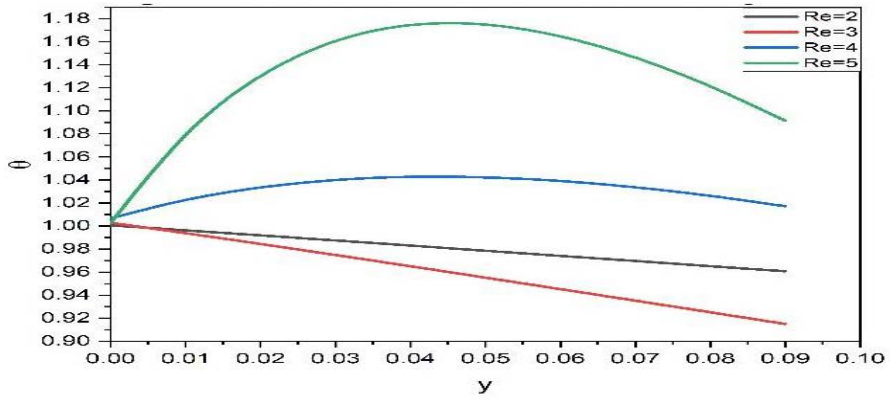

Fig. 14. Effect of Re for different values on temperature.

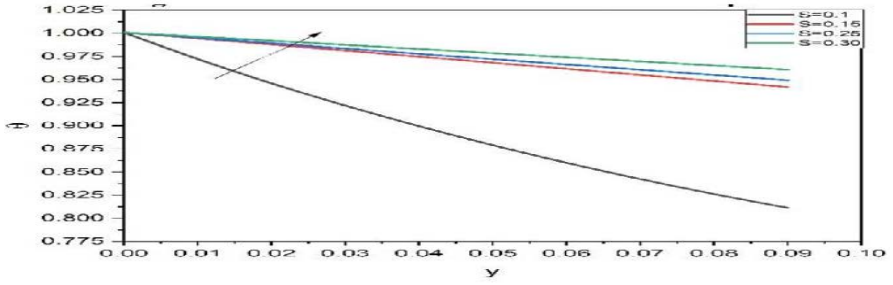

Fig. 15. Effect of S for different values on temperature.

Prandtl number plays a critical role in determining the shape of the temperature profile in fluid flow. Here it is evident that when $Pr < 1$, thermal diffusion dominates over viscous forces, i.e. heat is transported more efficiently than momentum. When $Pr > 1$ viscous forces dominates over thermal diffusion, i.e. momentum is transferred more effectively than heat.

The influence of Radiation parameter (R) on the fluid temperature with y is shown in Fig. 13. Here, it is seen that fluid temperature decreases with an increase in R.

It seems that the decrease in fluid temperature with increase in the value of R is a complex interplay of heat transfer, energy balance, temperature distribution, energy conversion efficiency and coupling of radiations in MHD.

From the graphical representation in Fig. 14, it is observed that fluid temperature decreases up to $Re = 3$ and after it starts increasing.

The Reynolds number can influence the temperature of fluid by influencing flow regime i.e. streamline to transit state and then become turbulent. High value of Reynolds number leads to more turbulent flow, affecting temperature distribution and enhancing Joule heating.

Figure 15 indicates the effects of the heat source parameter (S) rising, which are produces the increase in fluid temperature with y.

The heat source parameter typically indicates the strength or intensity of a heat source within a flow system. Increase in temperature with S may be the resultant of temperature distribution, Buoyancy effect, flow pattern and vortex formation.

CONCENTRATION

Variation of concentration distribution versus Eckert number (Ec) is displayed in Fig. 16. No significant change is observed in this figure as Eckert number (Ec) increases slightly. However, very small increase is shown in concentration.

As the Eckert number is just the ratio of two parameters i.e. kinetic energy to the enthalpy difference across the flow. The very small increase in concentration represents the equivalence of both the parameters.

Figure 17 depicts the effect of chemical reaction (Kr) on the concentration distribution of the flow field. The chemical reaction (Kr) is shows in Fig. 17. It seems that the complex interplay between fluid dynamics, magnetic fields, and chemical kinetics has resulted in reducing effect on the concentration of the flow field at all points.

Figure 18 displays the influence of cross-flow Reynolds number (Re) in the concentration profile w.r.t. y. It depends on the flow conditions and correlation between convection and diffusion. The fall of concentration with the increase of the cross-flow Reynolds number (Re) may be due to the presence of diffusion and convection in fluid flow.

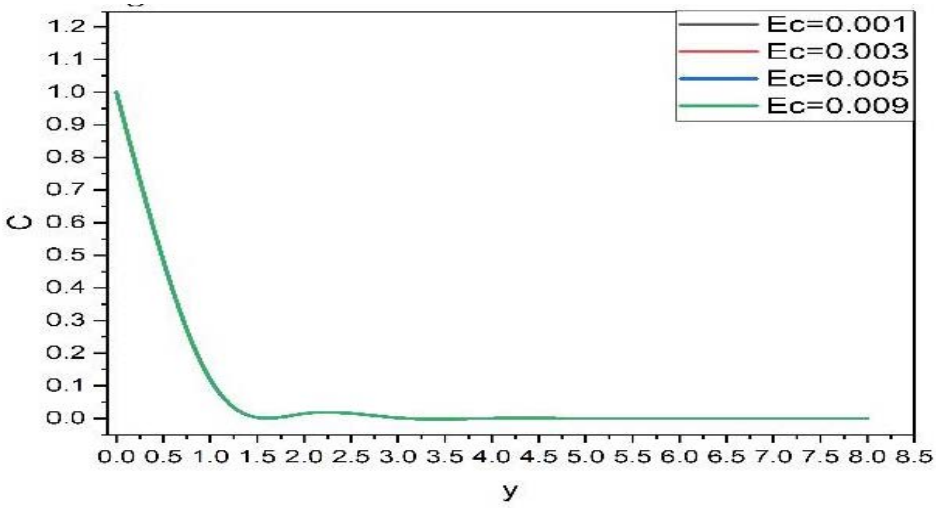

Fig. 16. Effect of Ec for different values on concentration.

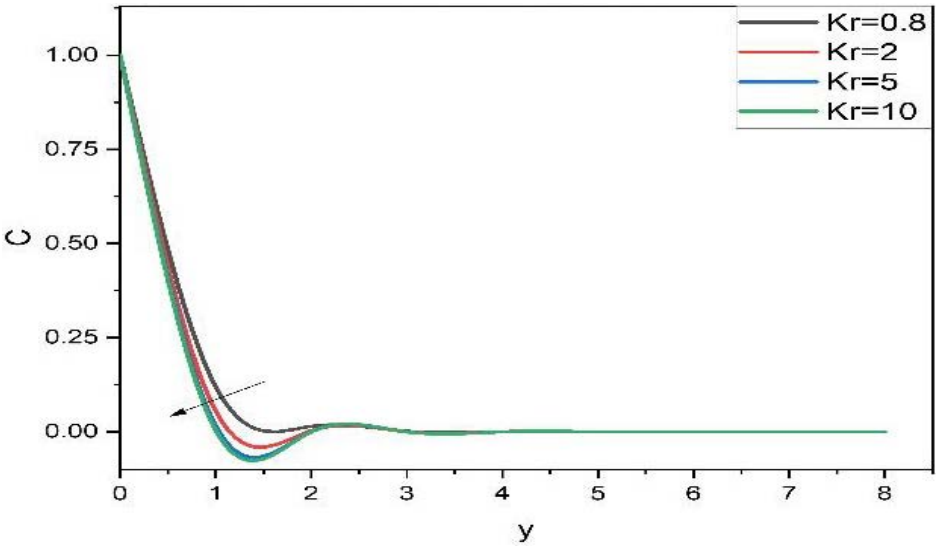

Fig. 17. Effect of Kr for different values on concentration.

The concentration profiles with different values of Schmidt number (Sc) is plotted in Fig. 19. From all graphs in Fig. 19, it is observed that the concentration increases sharply up to $Sc = 0.42$ and concentration decreases gradually afterward.

As the Sc is ratio of the momentum diffusivity (kinematic viscosity) to mass

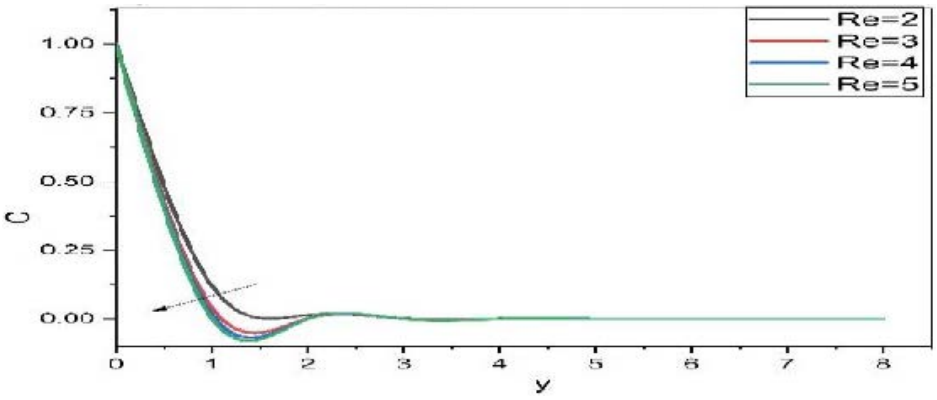

Fig. 18. Effect of Re for different values on concentration.

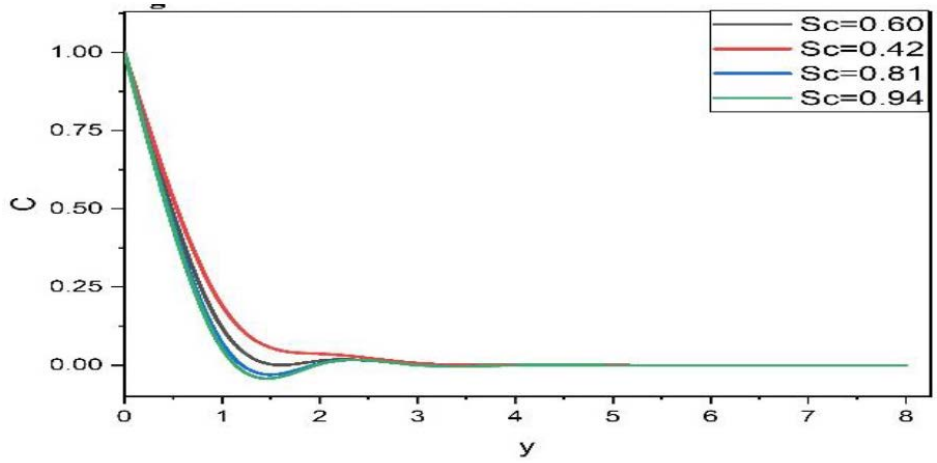

Fig. 19. Effect of Sc for different values on concentration.

diffusivity. The decrease of concentration after $Sc = 0.42$ may be due to imbalance in momentum and mass diffusivity.

Figure 20 demonstrates the distribution of concentration profiles in the fluid medium for different values of Soret number (Su). In this illustration it is observed that an increase in the Soret number (Su) decreases the concentration of the fluid which may be the result of enhanced mass transfer in the direction of the temperature gradient.

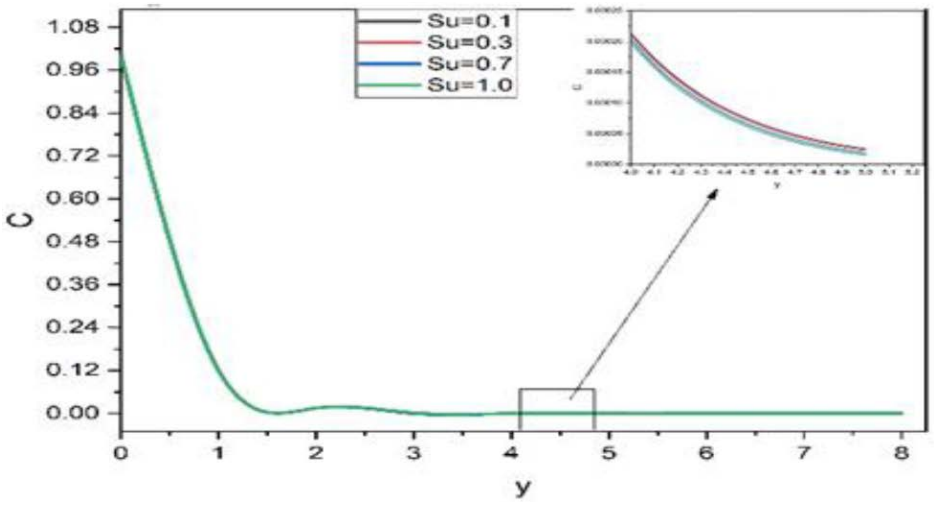

Fig. 20. Effect of Su for different values on concentration.

5 Conclusion

In the present work, various parameters influencing three dimensional free convective MHD flow through porous medium were analysed critically. The analysis of variation of velocity profile with various parameters revealed that the velocity profile of fluid flow improves with the increase in the values of fluid flow parameters Gm, Gr, Re, S where it decreases with increase in the values of Ec, Ko, Kr, M, and R. Also few parameters like Pr, Re shows pulsating trend of variation. It is also observed that increase of flow parameters Ec and S increases the fluid temperature whereas R has reciprocal effect. Small incremental increase in Re results in decrease in temperature of the fluid but the large increase of Re increases the fluid temperature. Increase in the values of Kr, Re and Su decreases the concentration of the fluid flow. No significant change is observed in the concentration of the fluid with the Eckert number (Ec). Very small increase of Schmidt number (Sc) shows increase in concentration of the fluid but large increase of Schmidt number (Sc) have reverse effect on it.

The variation of skin friction with Pr and Sc show similar pulsating behaviour whereas the Su and Ec influence the skin friction in opposite way. The effect Kr and Re on skin friction reflects the reciprocate variation. The effect of flow parameters R, Gr and M on skin effect reveals the similar pattern of variation. The Skin friction is a measure of the force exerted by a fluid moving along a solid boundary, and it is a complex interplay of various flow parameters which results in change of heat transfer mechanism, temperature gradient, temperature distribution, fluid density and viscosity.

The Nu and Nu_1 characterize the convective heat transfer between of fluids and different boundary conditions, fluid properties, or geometries of the fluid flow. The influence of various parameters shows either direct or inverse variation or independent behaviour due to combined effect of temperature distribution, energy conversion efficiency and enhanced mass transfer.

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